Poster 8

Fiber optic seismic sensing of the subsurface

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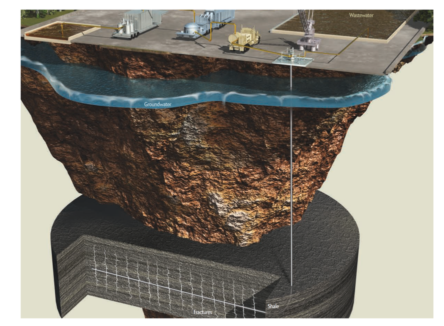
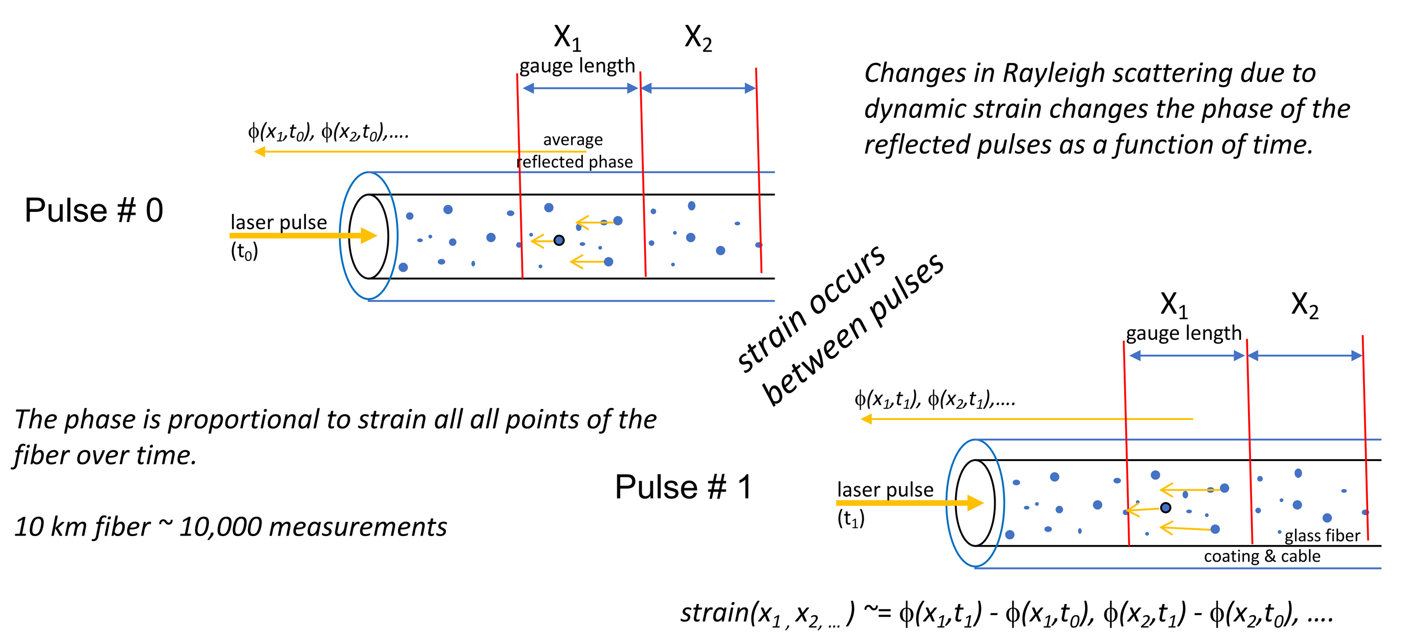
Fiber optic distributed acoustic sensors (DAS) are becoming a widely used tool for seismic sensing for both active and passive measurements. DAS sensors possess several advantages such as low-cost high spatial resolution and wide bandwidth response, but also includes disadvantages such as one component of measurement and a higher noise floor. Here we explore the components of the typical system response (interrogator, fiber/cable, and coupling) and the expected response along with an assessment of the potential for future improvements. Validation of the estimated response is ongoing using a custom interrogator and a fiber testbed. We then apply this understanding to measurements of local and regional events including full waveform modelling and earthquake parameters inferred from coda measurements using data from fiber sensors.



Unconventional oil and gas production
Image fractures and fluid

Fiber optic dynamic strain sensors allow the measurements of seismic and acoustic signals.
The nature of fiber allows new and novel measurements at high spatial resolution and in extreme conditions.
Further improvements are possible in the areas of improved modeling and sensor development.
LLNL possess the core capabilities to address these challenges.

Measuring strain with a telecom fiber and a laser



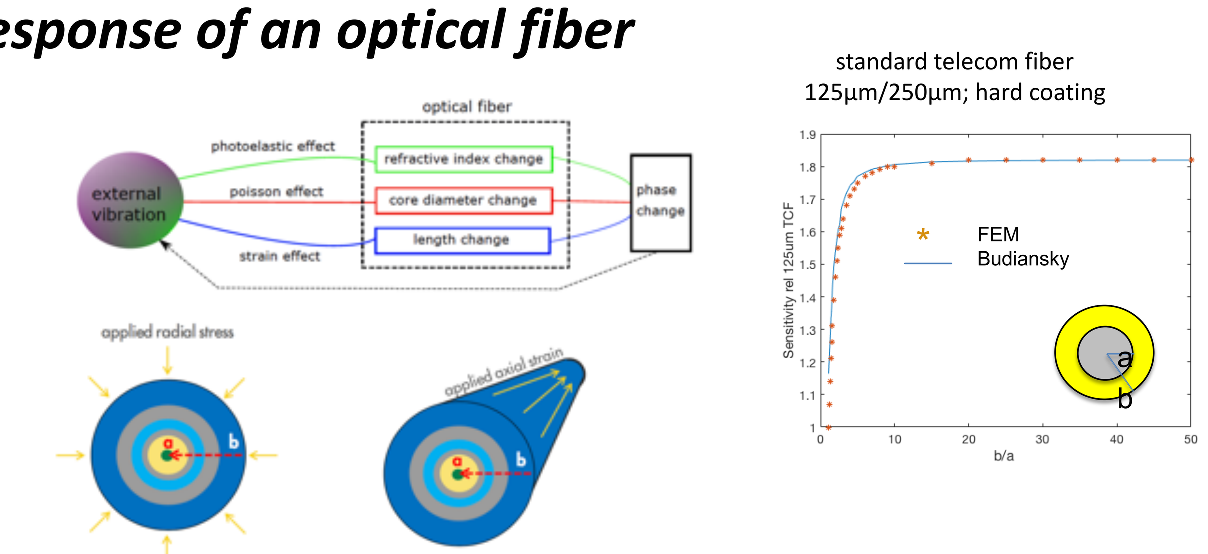
Changes in Rayleigh scattering due to dynamic strain changes the phase of the reflected pulses as a function of time.

The phase is proportional to strain all all points of the fiber over time.

10 km fiber ~ 10,000 measurements

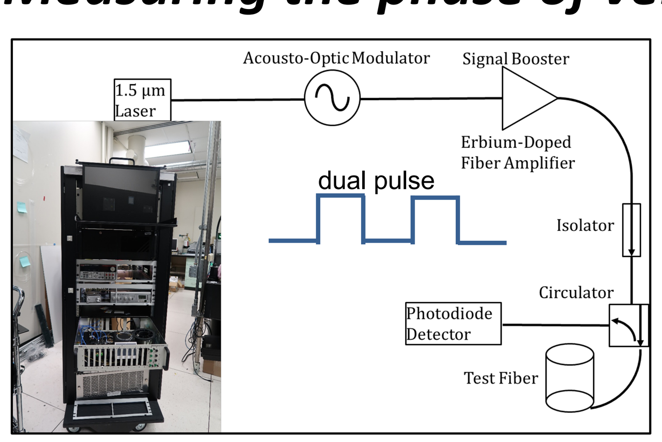
$strain(x_1, x_2, \_) \sim= \phi(x_1,t_1) - \phi(x_1,t_0), \phi(x_2,t_1) - \phi(x_2,t_0), \ldots$

Response of an optical fiber

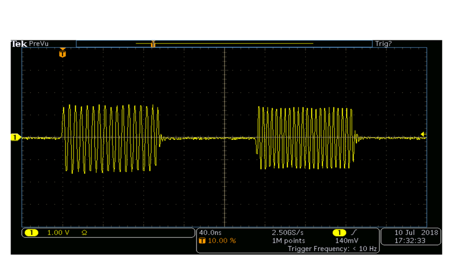


Fibers respond to both longitudinal and radial pressure, as well as changes in the refractive index. In solids, both longitudinal (~80%) and radial (~20%) may have an effect. In water, radial stress is the primary cause of the signal. Changes in the thickness of the coating will affect radial response.

Measuring the phase of very weak light signals



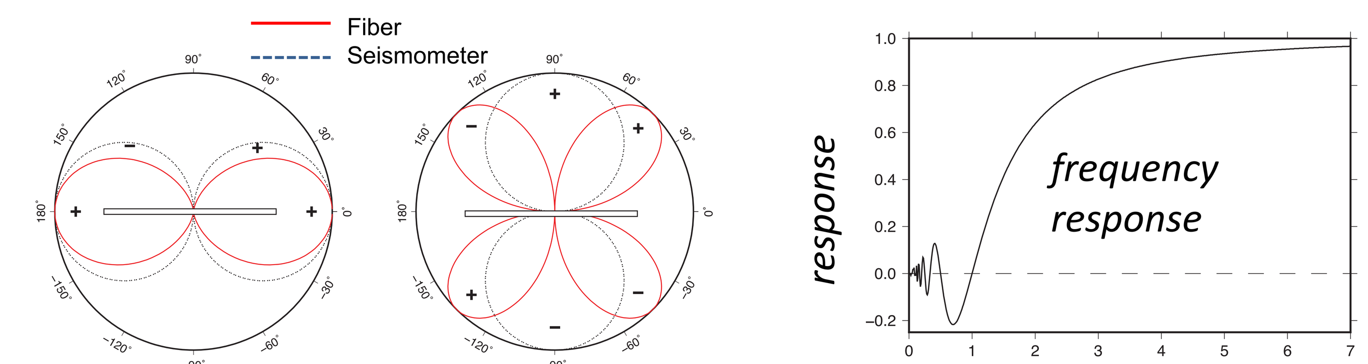
1) Send dual modulated pulse down fiber
2) Measure $\phi(x,t)$ [I,Q] from fiber (beat frequency of reflections)
3) Divided into channels for each section of fiber (not equal to gauge length)
4) Convert I,Q to phase, unwrap [post-processing]
5) Provides strain as a function of time for each channel



Dual-pulse system
Initial pulse at 1550.12 nm (diode laser)
Acousto-optic modulator (AOM) splits into two pulses with ~100 ns gap
Each pulse has different frequencies (170 and 230 MHz)
Upon reflection, these pulse beat together.
Returned signal is measured by photodetector
The phase of the returned beat frequency is proportional to the strain.
Challenges are recording data fast enough to disk.

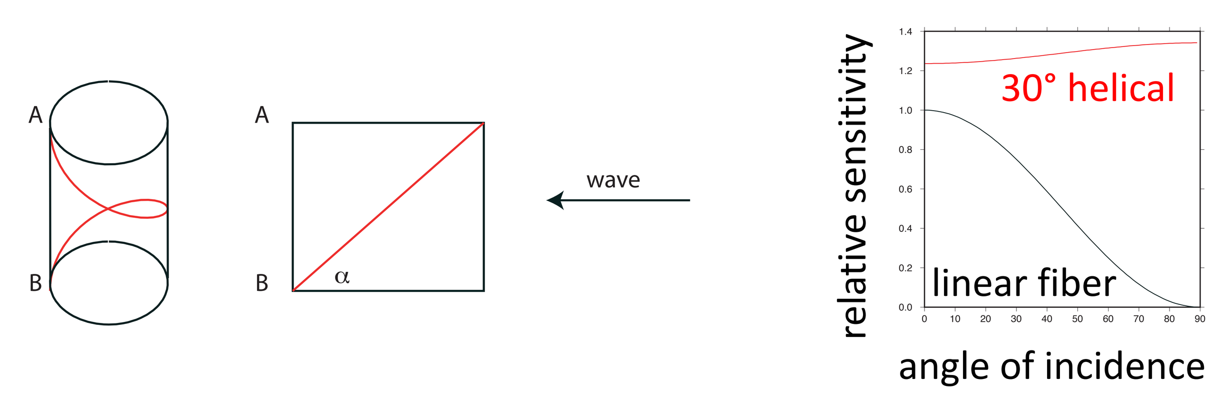
$$I = |E_1|^2 + |E_2|^2 + 2|E_1||E_2| exp\left[j\left(2\pi\left[|f_1 - f_2|t + \frac{2n\sigma\delta(z_1 - z_2)}{\lambda}\right]\right) + \theta_1 - \theta_2\right]$$

Sensor response to seismic waves: P and S



longitudinal (P wave) transverse (S wave) wavelength/gauge length

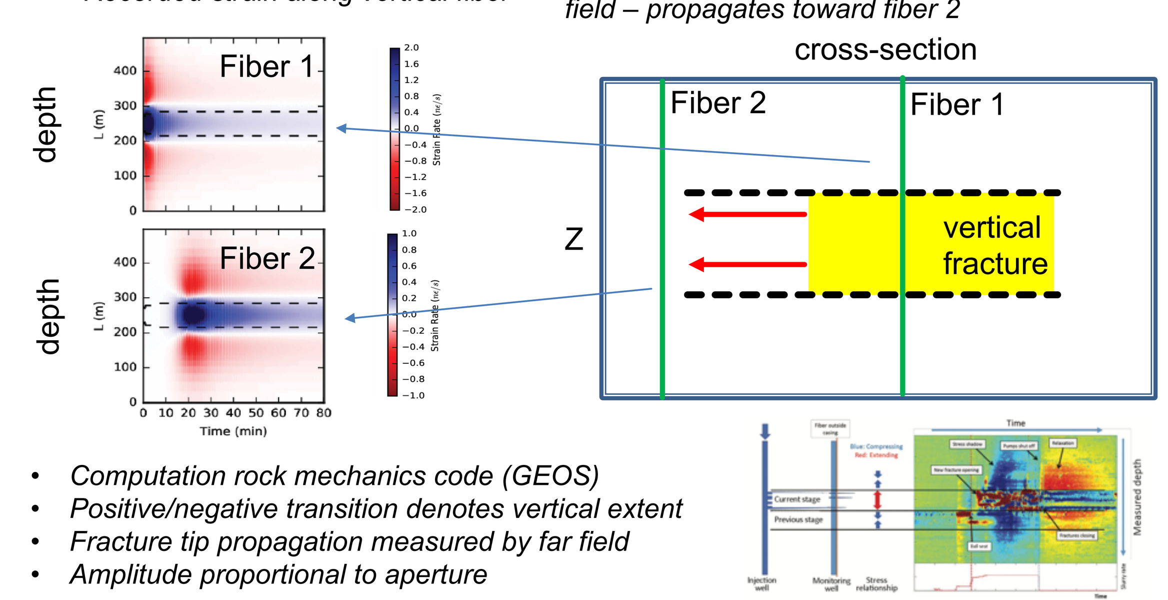
The fiber is a strain meters and therefore measures a tensor quantity rather than a vector quantity, as a standard seismic sensor does. For a linear fiber, this results in a directional response, which is not ideal for a seismic sensors. This can be alleviated by winding the fiber in a helix (or multiple helix) which events out the response. The fiber also suffers from spatial aliasing when the wavelength approaches the gauge length.



Subsurface and surface measurements

Recorded strain along vertical fiber

Fracture vertical extent limited by in situ stress field – propagates toward fiber 2

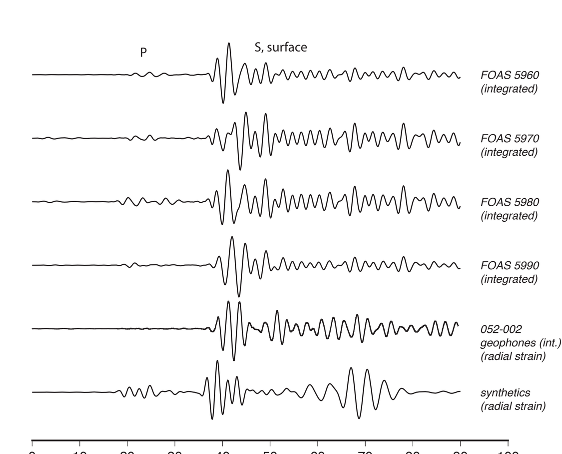


- *Computation rock mechanics code (GEOS)*
- *Positive/negative transition denotes vertical extent*
- *Fracture tip propagation measured by far field*
- *Amplitude proportional to aperture*

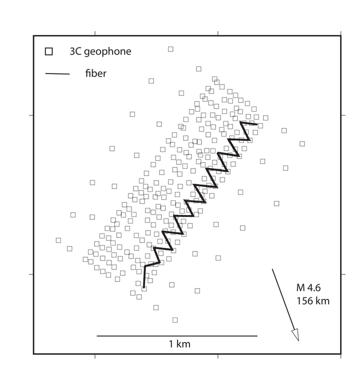
See Sherman et al, (2018)

Jin and Roy, 2017

The slim nature of fiber makes it ideal for measurements in a a subsurface well. Above are example of the strain field caused by an hydraulic fracture in an oil well and models of the strain as computed by a LLNL computation rock mechanics code.



Bandpass (0.25-0.50 Hz), trace normalized



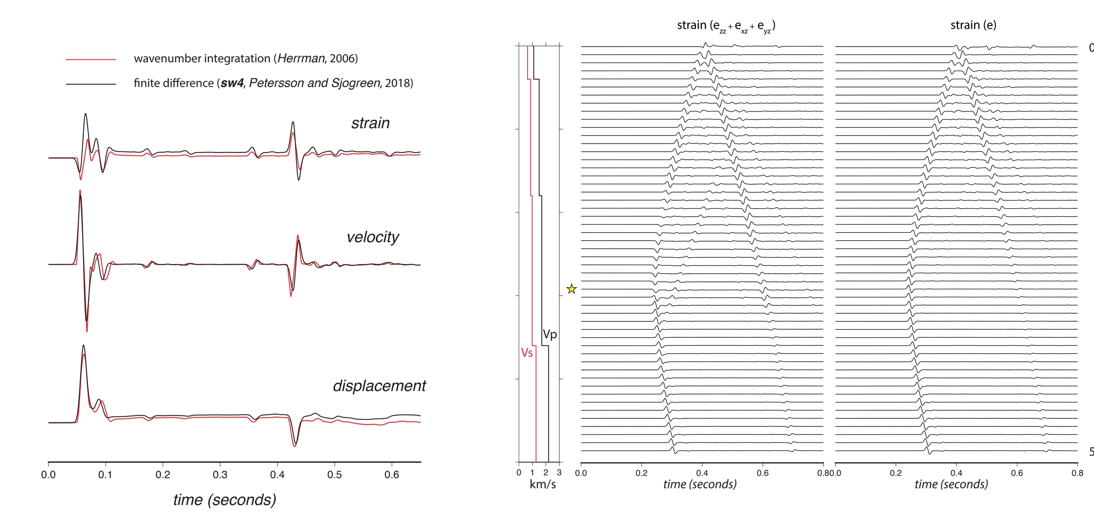
M4.4 regional event (~150 km)
Silixa linear fiber (strain-rate)
Data courtesy Wisconsin POROTOMO
Moment tensor solution courtesy UNR

Here we show an example of an earthquake collected by a fiber deployed on the surface. The fiber was col-located with geophones to compare response. Modeling yielded a good fit to the data, both fiber and geophone.

Next steps

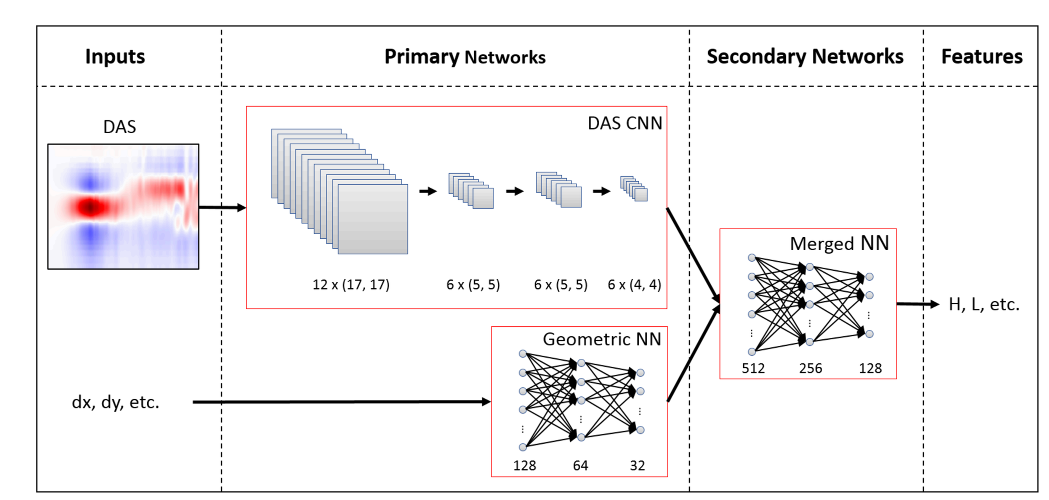
- Improved sensitivity
- Improved broadside response
- Quantitative understanding of coupling

First-pass synthetics of fiber in a borehole from nearby source



linear fiber helical*

Interpreting fiber data with machine learning



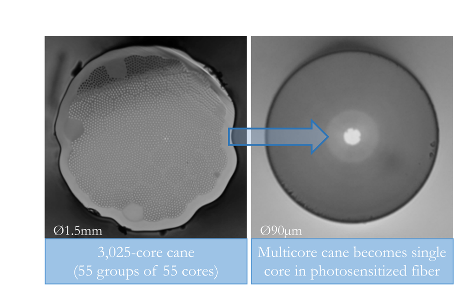
DAS – distributed acoustic sensor
CNN – convolutional neural net
NN – neural net

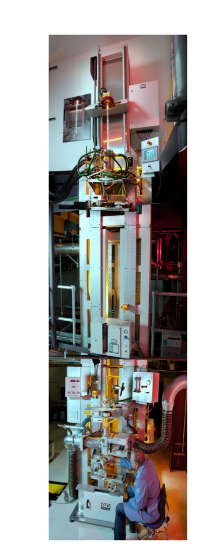
Engineered fibers for optimal response using the LLNL fiber draw tower

Increase fiber sensitivity with custom fibers

Change composition of fiber (doping) to increase photosensitivity

Irradiate fibers with high-energy pulses from a UV laser to write 'weak' Bragg pattern into their waveguide cores





Summary

- Optical fiber-based sensors are effective at measuring low and high-frequency seismic signals.
- Response differs from standard sensors, due signal type (strain), and instrument.
- We believe that although uncertainties remain, adequate responses can be estimated.
- We have successfully modeled observed signals; inversion is in progress.
- We expect that substantial improvements in capability are possible (multiple helix cables, high-temperature [>200 C] sensors, weak fiber Bragg, enhanced sensitivity.

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